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Annual Report

Contract Number N0014-90-J-1274

NUMERICAL SIMULATION OF NONLINEAR RECEPTIVITY IN BOUNDARY LAYER TRANSITION

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Period covered: October 1, 1989 - September 30, 1990

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This is the annual report on ONR - Contract No. N0014-90-J-1274. In this report the scientific research goals are described for both the research on active control of boundary layer transition and the research on nonlinear receptivity in boundary layer transition. The research was based on direct simulations using the complete Navier-Stokes equations. Some of the significant results obtained during the past year are discussed and plans for future research are specified.

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NUMERICAL SIMULATION OF NONLINEAR RECEPTIVITY IN BOUNDARY LAYER TRANSITION

a) *Description of Scientific Research Goals*

1. Active Control of Boundary Layer Transition

The control of the transition from laminar to turbulent flow is of primary interest in many engineering applications. Delay or acceleration of transition to turbulent flow may enhance or restrain the fluid mixing, heat transfer or reduce the friction drag on aerodynamic bodies. In this research ~~project~~ ~~we~~ consider basically two different approaches to influence the transition process. The first approach is based on the idea of changing the stability characteristics of the base flow. This approach we categorize as passive control. Examples of passive control include constant suction or blowing of fluid at the wall, favorable pressure gradient along the streamwise flow direction, or constant heating of the wall surface.

The second approach to influence the transition process ~~we~~ term active control. There the disturbance waves which are amplified because of the instability of the base flow are directly manipulated. The feasibility of this second approach and its potentially considerable advantages were demonstrated in the experiments by Liepmann et. al. at the California Institute of Technology. In ~~these~~ experiments amplitude and phase controlled disturbances were produced by thin metal strips or actuators that were flush mounted on the surface of a flat plate. With proper phases and amplitudes, both naturally occurring and controlled (forced) Tollmien-Schlichting waves could be attenuated and thus the transition process delayed.

Emphasis of the present research is on the second approach. Here, we are numerically simulating the above mentioned experiments by Liepmann et al. The motivation for this is three-fold: With a detailed numerical investigation we should be able to substantiate or dismiss claims concerning the effectiveness of active control using heating strips for delaying transition. Secondly, and more importantly, with a numerical simulation we hope to gain insight into the physical mechanisms of how localized heat disturbances are transformed into Tollmien-Schlichting waves in a boundary layer. After understanding this particular "receptivity" mechanism, we hope to be able to suggest and study other and possibly more effective means for controlling the transition process. Thirdly, in the experiments of Liepmann et al, only control of two-dimensional

waves were considered. Here, however, we also will be able to investigate control of the three-dimensional wave development of the transition process.

The numerical simulations for this research are based on numerical solutions of the complete Navier-Stokes equations coupled with the energy equation using Class VI Supercomputers CRAY-YMP and CRAY-II. At this stage of our research we have developed a series of numerical codes to study the aforementioned scientific goals. According to the flow structure under study the computer codes can be divided in two categories, i) the two-dimensional base and disturbance flows and ii) the two-dimensional base and three-dimensional disturbance flow.

2. Nonlinear Receptivity in Boundary Layer Transition

The laminar-turbulent transition in a boundary layer is in many cases initiated by a process which is generally referred to as receptivity. This term denotes the various mechanisms by which external or internal disturbances are transformed into instability waves within the boundary layer. Of practical interest are disturbances such as sound, free stream turbulence, or unsteady pressure gradients.

During the last decade, experiments and theoretical approaches have yielded some insight into linear receptivity in situations where transition is initiated by "controlled" single frequency disturbances of small amplitude. However, for many engineering applications an understanding of the nonlinear receptivity mechanisms is more important, because in practical situations the external disturbances are often very large and contain a broad band of frequencies.

There are still no adequate mathematical tools available to investigate these nonlinear mechanisms on a theoretical basis, and they are very difficult to study experimentally. Therefore, we intend to investigate relevant aspects of nonlinear receptivity by direct numerical simulation solving the complete Navier-Stokes equations. The first phase of this research is based on numerical solutions of the incompressible, two-dimensional, unsteady Navier-Stokes equations in the velocity-vorticity formulation. An existing computer program to solve these equations has been adapted to investigate boundary layer receptivity to free stream perturbations.

Since we need to study flows over bodies with non-trivial geometries, we plan to implement a curvilinear coordinate system in the program, using either analytically or numerically generated coordinate grids.

b) *Significant Results in the Past Year*

We continued our effort to control wave packet disturbances. Emphasis at this stage was placed on the control of three-dimensional wave packet disturbances. In the later stages of the transition process the instability waves become three-dimensional. and a preferred spanwise structure can be identified depending on the amplitude level of the disturbances.

Fig. 1 shows a sketch of the computational domain over the flat plate. The first heater strip activates a pulsed disturbance in the flow field with a temperature fluctuation. The heater strips are assumed to consist of a spatial mean temperature which is uniform in spanwise direction with a sine-square distribution in streamwise direction A temperature fluctuation is then superimposed in a finite duration whose amplitude is varying sinusoidally in spanwise direction. For the present computation the spanwise wavenumber is $\gamma = 20$. The duration of the temperature pulse is chosen so that its spectrum (input spectrum) is very broad with an amplitude maximum for the most unstable frequency (F_1 = 1.4) as given by the linear stability theory. The width of the heater strip is chosen as half the wavelength corresponding to the most unstable frequency.

A spanwise decomposition of the flow is shown in Fig. 2. Shortly after the end of the wave packet excitation at timestep 130 (the duration of the excitation is until timestep 120) the streamwise disturbance velocity contours indicate a wave packet for both the two- dimensional (k=0), and the three- dimensional (k=1) component. In this early stage the spatial selection of the unstable frequencies is not yet fully completed. However the k=1 component appears to have dispersed already more than the k=0 component.

A contour plot of the streamwise and spanwise disturbance vorticity distributions is shown in Fig. 3. These contours are taken in a horizontal plane at the flat plate surface (wall vorticities). The spanwise extend covers two wavelenghts. The spanwise vorticity maxima point out the spanwise wavelength of the temperature fluctuation during excitation. The maxima of the streamwise vorticity follow in between the maxima of the spanwise vorticity. The streamwise vorticity vanishes where the local spanwise derivative of the spanwise vorticity is zero.

For the attenuation of three-dimensional disturbances in an effectively two-dimensional flow one needs to primarily concentrate on the control of the spanwise vorticity component assuming the flow is still in early three-dimensional breakdown

stage. The amplitude and phase spectra of the spanwise wall vorticity are shown in Fig. 4. The spectra are recorded at several streamwise positions downstream of the activator strip. At the station closest to the activator strip the spectra for both the k=0 and k=1 component are still very broad similar to the temperature input spectrum. However further downstream the spectra indicate the selection mechanism of the boundary layer. The very high and very low frequency components are strongly damped and the characteristic dome shaped spectrum appears where the intermediate frequency components are most amplified.

The amplitude spectrum of the k=1 component shows a sharp minimum at the frequency $F = .75$. The phase spectrum in the neighborhood of this frequency undergoes a rapid phase change of π, so that modes in the vicinity of this trough cancel each other out. The region of amplification for the k=1 spectrum is shifted to lower frequency components compared to the k=0 spectrum and the amplification rates are also reduced. This is in good qualitative agreement with three dimensional linear stability theory.

c) *Plans for Next Year's Research*

(i) Continue to simulate active control of three-dimensional waves using wave packet disturbances.

(ii) Investigate control of boundary layer using transfer function approach

(iii) Investigate effect of the two- dimensional control versus three- dimensional control and a combination of both on the growth of the wave packet disturbance

(iv) Perform a numerical simulation of a receptivity experiment by Kendall† to study the mechanisms by which a traveling pressure field in the freestream excites disturbance waves in a boundary layer. First, this should enable us to check the validity and accuracy of our code when applied to boundary layer receptivity. Second, we hope to gain insight into the specific receptivity mechanism, and to find answers to the questions that were left open by the experiment.

† Kendall, J.M., *Experimental Study of Laminar Boundary Layer Receptivity to a Traveling Pressure Field*, AIAA Paper 87-1257, 1987

(v) Investigate the effects of very high local vorticity concentrations in the freestream on the receptivity of a flat plate boundary layer.

Figures

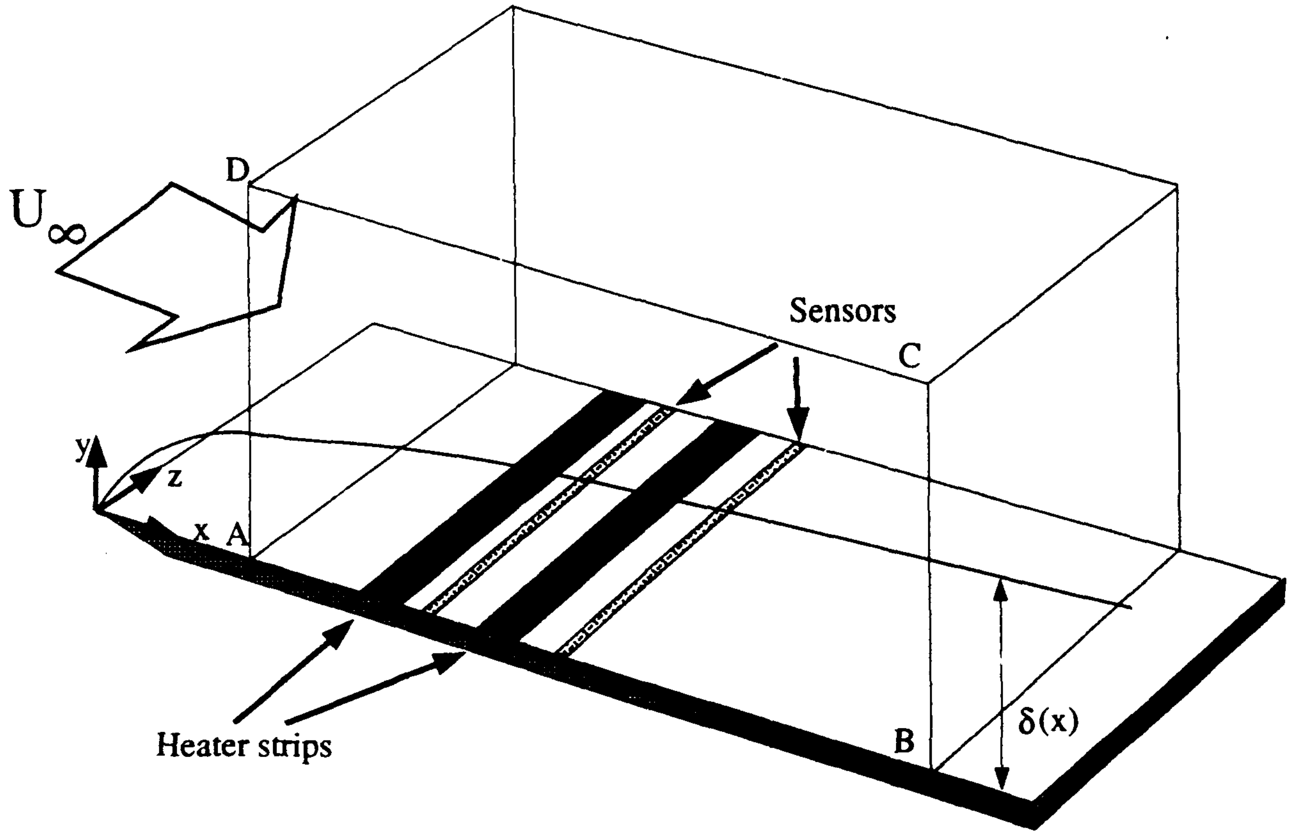


Fig. 1 : Integration domain showing the location of heater strips

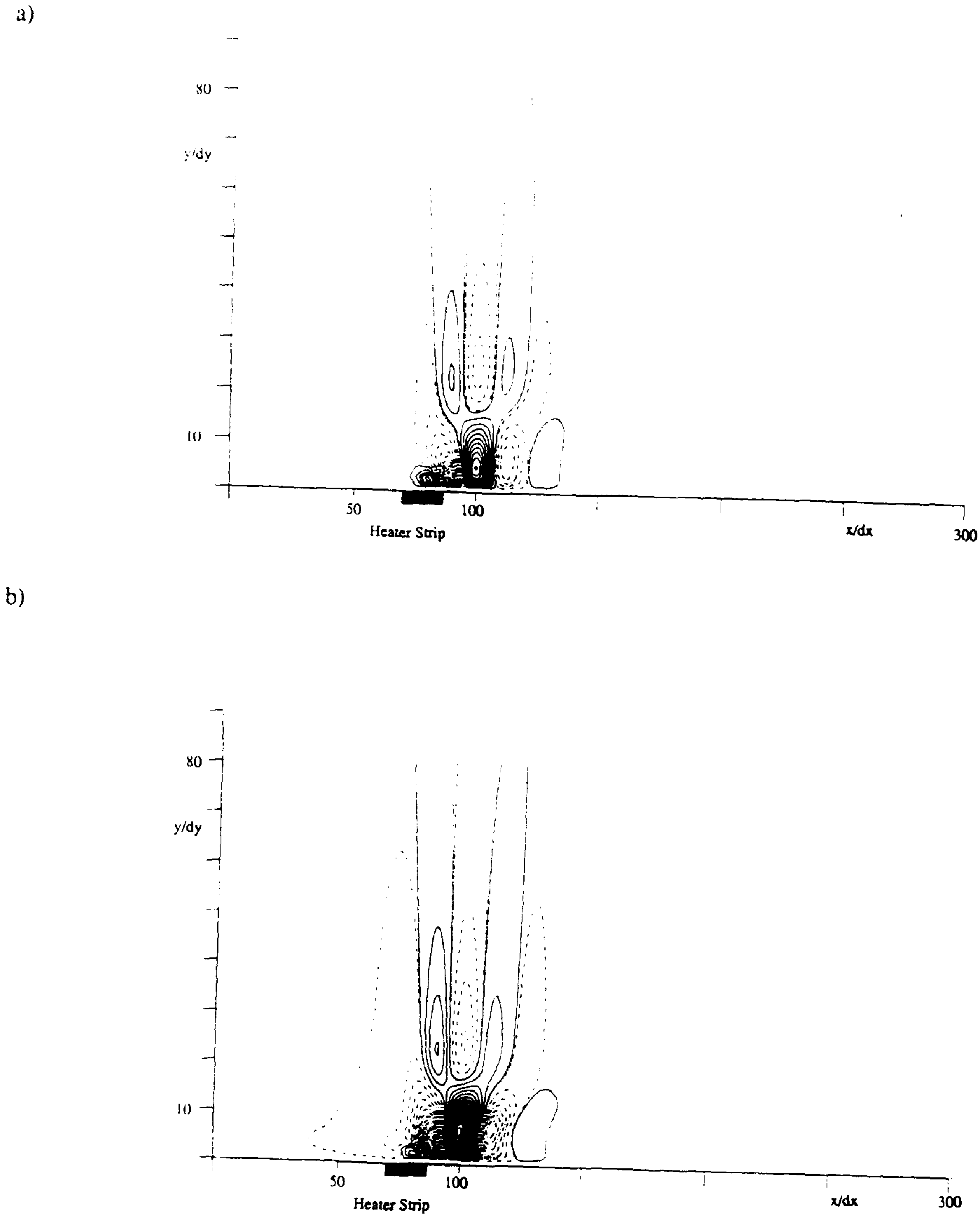
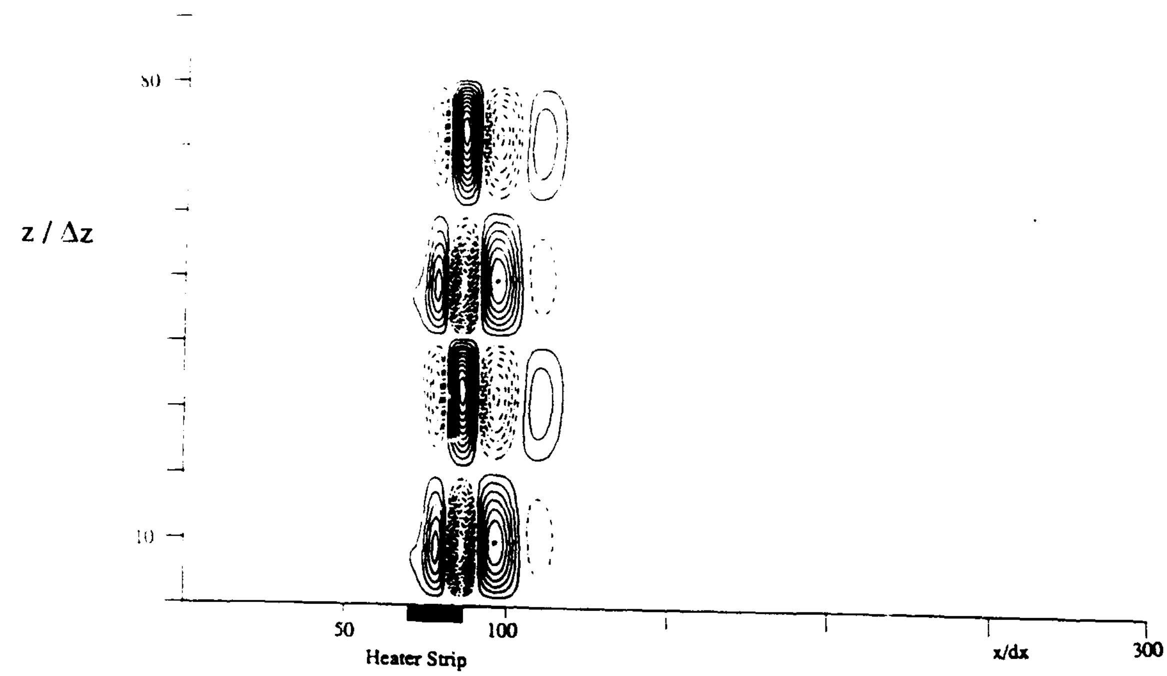


Fig. 2: Streamwise disturbance velocity component at $t/\Delta t = 130$ for a) the two-dimensional (k=0) component and b) the first three dimensional (k=1) component.

a)



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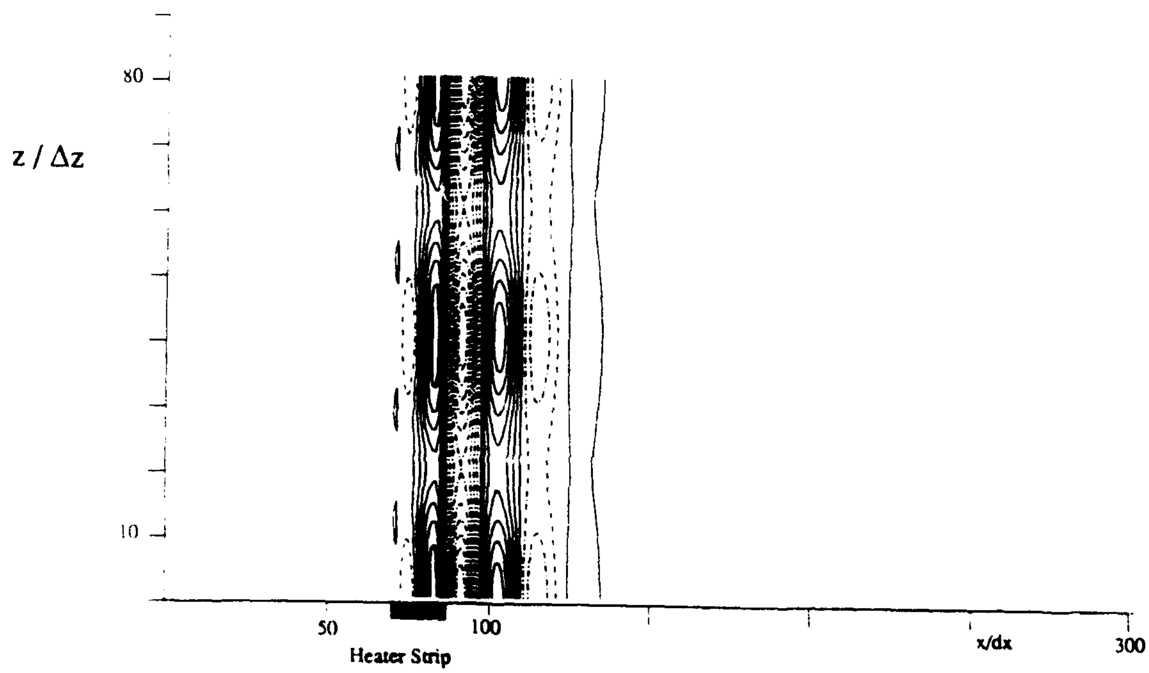

Fig. 3: Wall vorticity in the horizontal plane at $t/\Delta t = 130$ showing two spanwise perioas for a) the streamwise component and b) the spanwise component.

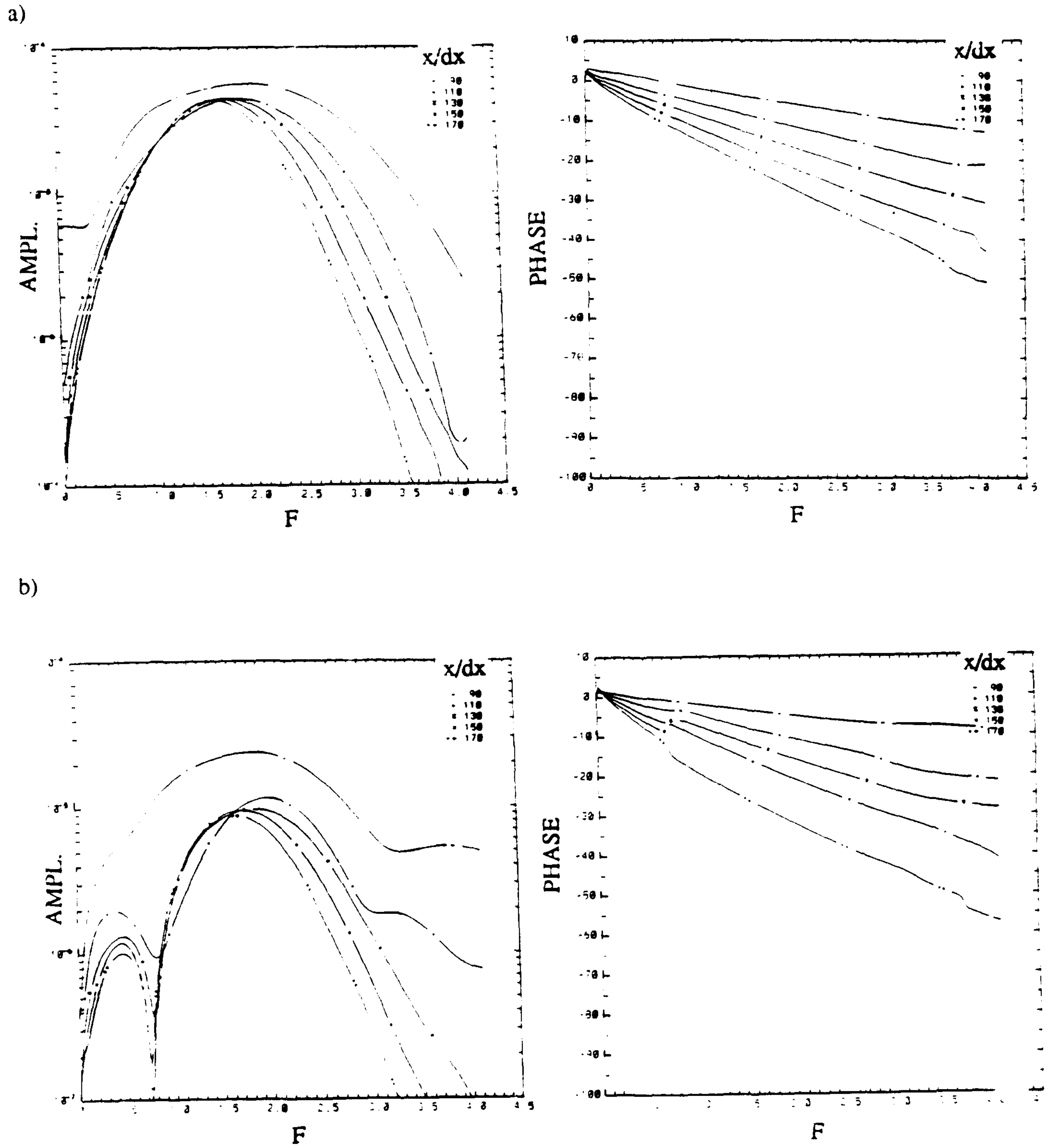

Fig. 4: Amplitude and phase spectra of the spanwise wall vorticity at several streamwise positions x/Δx for a) the two dimensional (k=0) and b) the first three dimensional (k=1) component.